AD-A266 812

ON PAGE

OMB No. 0704-0188

Public gathe collect Davis

ge 1 hour per response, including the time for reviewing instructions, searching existing data sources, collection of information. Send comments regarding this burden estimate or any other aspect of this ashington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson agement and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. A

June , 1993

3. REPORT TYPE AND DATES COVERED
Final Report 1 Nov 90 - 30 May 93

4. TITLE AND SUBTITLE
The further development and refinement of an Expert-Systems Approach to the Creative Design of Mechanisms and Mechanical Systems (with application to robotic end effectors

5. FUNDING NUMBERS
DAAL03-90-G-0130

6. AUTHOR(S)
Professor Ferdinand Freudenstein and Dr. David Hoeltzel

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Columbia University, New York, NY 10027

8. PERFORMING ORGANIZATION REPORT NUMBER

JUL 12 1993

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 21945.3-EG

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Re: Research of Professor Freudenstein and students (Hong-Jen Chen & Don Lin). The research has been concerned with a comprehensive analysis of robotic end effectors including frictional energy dissipation and rigid-body as well as flexible elements. The design analysis involves a set of nonlinear simultaneous equations of quantifying such phenomena as preloads, internal forces, frictional drag, kinematic and dynamic performance and optimization criteria, energy losses and efficiency. The analysis facilities the optimization of robotic systems in the design stage. A new concept, which we may call a cylindrical actuator, was developed in the course of the research (and communicated to ARO) and may have significant applications, both in robotics, as well as in other areas of mechanical design.

04

93-15735

14. SUBJECT TERMS
Robotics, robotic end effectors, design optimization

19

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

# THE FURTHER DEVELOPMENT AND REFINEMENT OF AN EXPERT SYSTEMS APPROACH TO THE CREATIVE DESIGN OF MECHANISMS AND MECHANICAL SYSTEMS

FINAL REPORT

U.S. ARMY RESEARCH OFFICE
CONTRACT # DAAL03-90-G-0130

COLUMBIA UNIVERSITY
NEW YORK, NY 10027

APPROVED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

# TABLE OF CONTENTS


Foreword.....2

PART A: Research of Professor Freudenstein and Graduate Students

Statement of Problem Studied.....4

Summary of the Most Important Results.....4

List of Participating Personnel and Advanced Degrees Earned while Employed on the Project.....7

Bibliography.....8

Appendix.....9-10

PART B: Research of Dr. David Hoeltzel and Graduate Student

Statement of Problem Studied.....12

Summary of the Most Important Results.....12

List of Participating Personnel and Advanced Degrees Earned while Employed on the Project.....14

PART C: Publications.....15



Accession For
NTIS GRA&I
DTIC TAB
Unannounced
Justification
By
Distribution/
Availability Codes
Dist Avail and/or Special
A-1

## FOREWORD

I am deeply grateful to the Army Research office for the support of my research for close to three decades. This support has enabled me, together with my students to engage in significant and challenging research. This in turn has enriched my career in many ways, including teaching, research and professional practice. I am now approaching a new phase in my life after nearly forty years of teaching and research and if I can be of help to the Army Research Office in any way, I hope you will let me know.

Sincerely,

Ferdinand Freudenstein

(Prof.) Ferdinand Freudenstein

# PART A

## RESEARCH OF PROFESSOR F. FREUDENSTEIN AND GRADUATE STUDENTS

## STATEMENT OF PROBLEM STUDIED

This involves the extension of the creative design methodology which has been previously developed (i.e, the creative design of mechanisms according to the separation of kinematic structure and function), so as to include both rigid-body elements, as well as elastic, inelastic, stretchable and intermittent elements, with applications to the design of robotic end effectors.

## SUMMARY OF THE MOST IMPORTANT RESULTS

### (a) THE COMPUTER-AIDED DESIGN OF ROBOTIC END EFFECTORS WITH RIGID, AS WELL AS ELASTIC ELEMENTS (DON LIN GRADUATE STUDENT) AND PRINCIPAL INVESTIGATOR).

This research concerns the design analysis of robotic end effectors via Lagrangian mechanics, including inertia forces, viscous damping forces, frictional drag, energy dissipation and joint reactions, (including both rigid-body, as well as elastic, deformable and intermittent elements). This involves the research of Don Lin (doctoral student) and the principal investigator. The analysis utilizes Lagrangian multipliers and force/torque analysis for the determination of the external and internal forces and torques of the system. The computation involves a set of 54 simultaneous equations in as many unknowns, the analysis of Coulomb friction being nonlinear, in view of the motion reversals which may occur. Hence continuous monitoring of the forces and their directions is required. The resulting analysis thus yields preloads, internal forces, frictional drag and energy losses. In turn, this information is highly useful in the performance optimization of these components. In this connection an application has been investigated involving an industrial type of cutting operation involving a cutter in combination with a four-bar dwell mechanism and a geneva type of intermittent-motion mechanism. By way of example of an unexpected insight, we have discovered that the type of screw (male or female) can affect the directions of the frictional forces - a seemingly elementary, but hitherto unused insight. And by treating the gripper dimensions as variables minimum frictional energy loss can be achieved.

### (b) NEW ROBOTIC ACTUATOR CONCEPT #1 (HONG-JEN CHEN (GRADUATE STUDENT) AND PRINCIPAL INVESTIGATOR)

In the course of our research a new robotic end effector or actuator concept has evolved, which we call the cylindrical actuator (and which we have reported to the Army Research Office). Figs. 1a, b illustrate this concept. The actuator has two degrees of freedom (rotation and translation about and along the cylinder axis) and the following characteristics:

1. Multiturn variable - pitch cylindrical cam.
2. Reversible actuation.

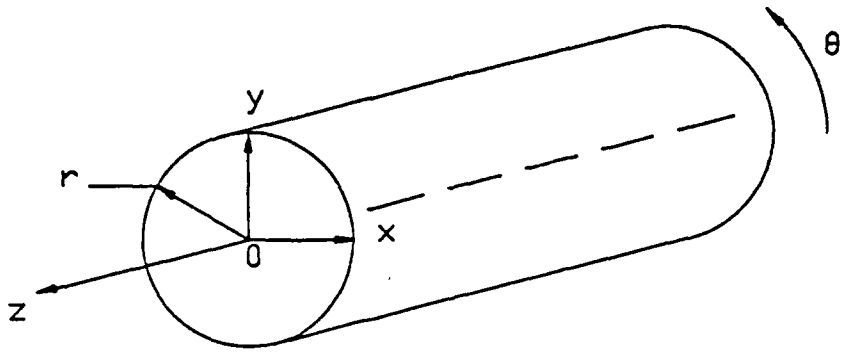


FIG. 1a: CYLINDER GEOMETRY

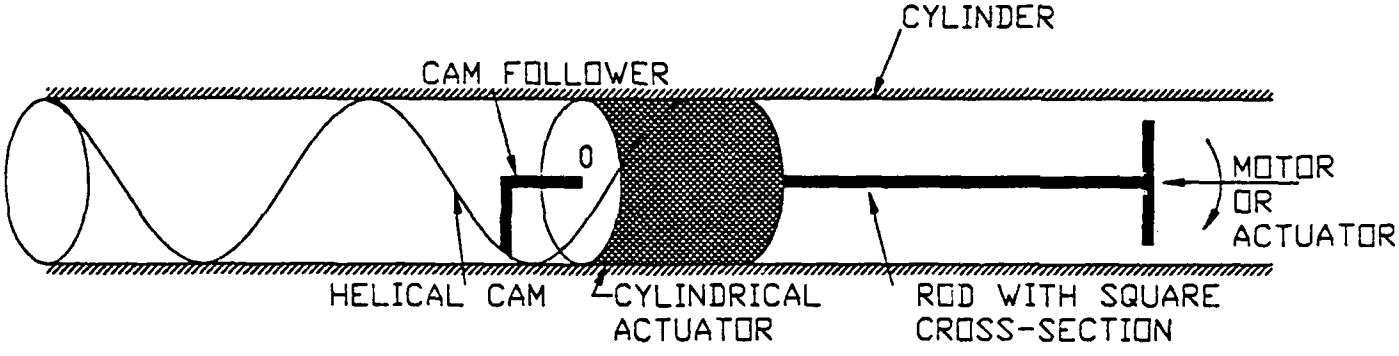


FIG. 1b: ROBOTIC END EFFECTOR AND/OR ACTUATOR

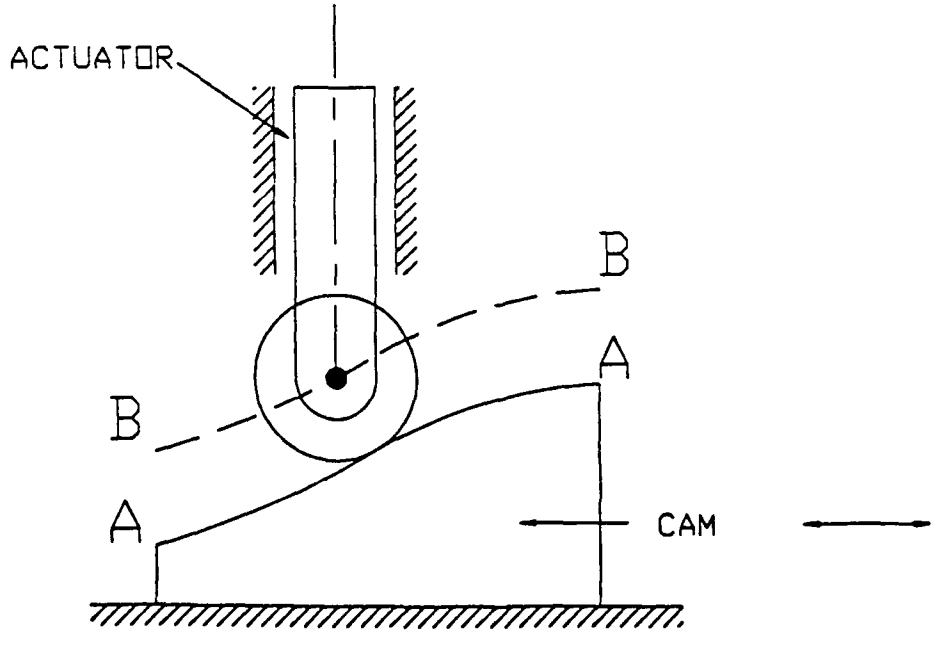


FIG. 2: CAM-TYPE ACTUATOR

3. Can be used in a variety of robotic applications.
4. Can be motor driven or hand actuated.
5. Positive motion in both directions.
6. Does not require a return spring.
7. Can be used to get into "inaccessible" regions.
8. Can be designed for desired displacement vs. time functions (i.e,. a controlled variable - pitch displacement).
9. Excellent dynamic balance.
10. Can be designed for positive oscillating and/or return motions.
11. Has a minimum number of parts.
12. Applications include manufacturing, paper cutting, material cutting, food slicing and others.
13. There are also potential military applications, as well as machining applications involving boring, drilling and turning.

Referring to Fig. 1a, let A(x,y,z) denote a general point on the cylinder with origin at O and coordinate axes as shown. Using polar coordinates (r,q), we then have:

$x = r\cos\theta$

$y = r\sin\theta$

and $z$ = axial displacement.

The cylinder motion can then be analyzed for displacements, velocities and accelerations, while for prescribed cylinder motions the corresponding helical cam curve can readily by synthesized.

(c) NEW ACTUATOR CONCEPT #2 : THE CAM ACTUATOR (HONG-JEN CHEN (GRADUATE STUDENT) AND PRINCIPAL INVESTIGATOR).

In the course of our research it became evident that while cam-follower systems are not usually associated with robotics, they can also be advantageous in the area of robotics. The classical Hrones model for cam-follower systems in the case of a horizontally translating cam with a vertically moving roller follower is shown in Fig. 2 in which A-A is the cam curve and B-B is the trajectory of the center of the follower. For a given cam curve we have obtained closed-form algebraic solutions for follower displacements, velocities and accelerations. Such a development in cam design is both innovative and useful, since it permits the computer-aided cam profile optimization in the design stage. When it is realized that cam followers can also be used as robotic actuators and that sophisticated cam curves are increasingly synthesized and analyzed algebraically (for effective design automation), their usefulness in robotic applications is likely to show a corresponding increase.

(d) SENSITIVITY STUDIES

This involves a new concept in sensitivity studies: the development of a quantitative approach to the optimization of tolerances (in engineering drawings of mechanical components and systems) in the design stage. The basic principle can be explained qualitatively as follows. Suppose we consider a two-dimensional mechanism with turning pairs and sliding pairs and one degree of freedom. In the presence of tolerances, clearances and offsets we can replace the turning pairs and sliding pairs by ball joints and other element pairs, (such as cylindrical pairs) in many cases, such that the mechanism is converted to an equivalent three-dimensional mechanism without tolerances or clearances. The difference between the displacements of the original and the derived mechanism will then be a measure of the effect of the tolerances and/or clearances involved. The Appendix summarizes the basic principles involved.

If I may be excused for what may seem a peripheral comment, I might add that to the extent that my technical career has been creative, it has on several occasions led to concepts seemingly unrelated to the particular research involved at the time, but it has always surfaced after a period of deep thought. In conclusion I wish to express my deep gratitude to the Army Research Office for the challenging and thoughtful research assignments which I have received in the course of approximately twenty-five or more years.

6. LIST OF PARTICIPATING SCIENTIFIC PERSONNEL

| | | |
|---|---|---|
| (i) | Mr. Hong-Jen Chen | (Graduate Student) |
| (ii) | Mr. Don Lin | (Graduate Student) |
| (iii) | Professor F. Freudenstein | (Principal Investigator) |

ADVANCED DEGREES EARNED WHILE WORKING ON THE PROJECT:

| | | |
|---|---|---|
| (i) | Hong-Jen Chen: | M. Phil. - May 1993 |
| (ii) | Don Lin: | M. Phil. - Fall 1992 (Ph.D. expected December 1993) |

BIBLIOGRAPHY

1. "On a Theory for the Type Synthesis of Mechanisms," by F. Freudenstein Proc. Eleventh International Congress of Applied Mechanics, Springer, 1966 - pp. 420-428.

2. "Creation of Mechanisms According to Kinematic Structure and Function," by F. Freudenstein and E. R. Maki, J. Environment and Planning B, 1979, Vol. 6, pp. 375 -379.

# APPENDIX

## A QUANTITATIVE APPROACH TO THE DETERMINATION OF THE EFFECTS OF TOLERANCES AND CLEARANCES ON THE DISPLACEMENTS OF MECHANISMS.

The quantification of the effects of tolerances and/or clearances in mechanisms constitutes a complex problem. Currently there is no theory which can quantify these effects and hence the quality of designs with tolerances and clearances remains a matter of judgement and experience. It is well known that at high speeds, impact and inertial forces can be very high, while if no clearances are permitted the mechanism will bind. This dilemma between the two extremes does not have a simple solution.

One approach, however, which has occurred to the principal investigator involves the following thinking.

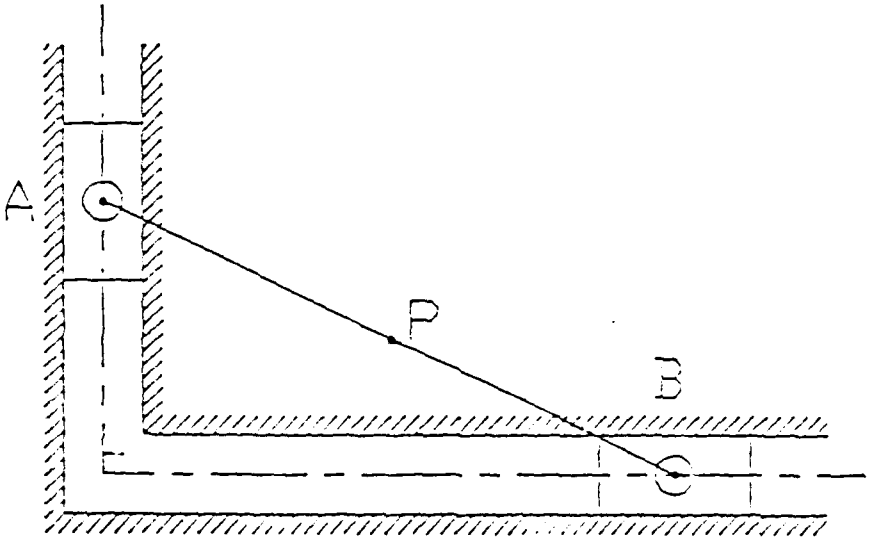


FIG. 3a: CARDANIC MOTION

Consider, for example, the case of cardanic motion, as in Fig. 3a. It is well known that any point, P, on the floating link describes an ellipse, (and Fig. 3 is two-dimensional.)

Suppose, however, that the trajectories of points A and B in their respective sliders is not quite coplanar, i.e.: the sliders are offset by a small distance, e, say as shown in Fig. 3b (exaggerated so as to be clearly visible). The question then arises as to the nature of the trajectory of the mid-point P of AB, say. In this case we replace the two prismatic pairs associated with the sliders by two ball joints ($S_1$ and $S_2$), where $S_1A = AS_2$.

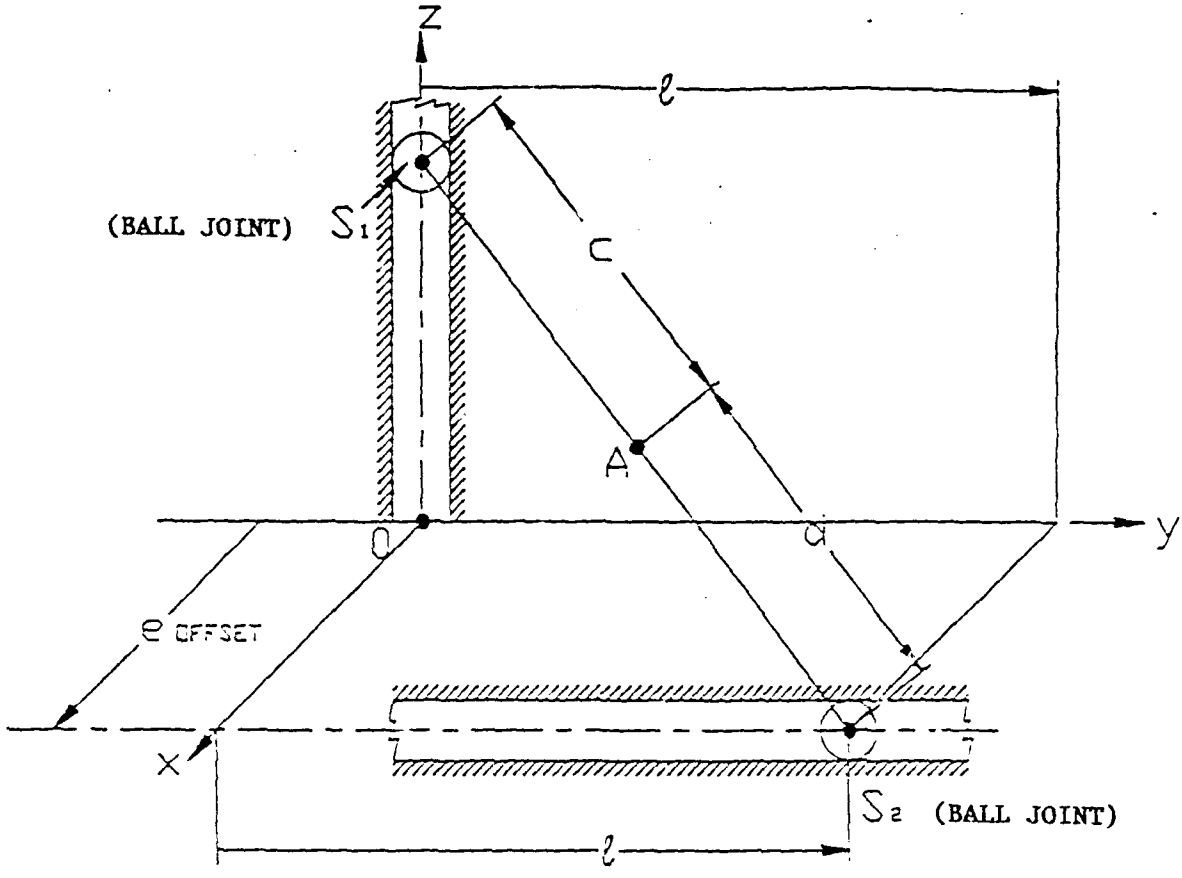


FIG. 3b: MODIFIED MOTION DUE TO OFFSET

The mechanisms has now become a three-dimensional mechanism with the offset dimension, e, exaggeratec so as to make the nature of he modeling clear. The trajectory of point A has changed. In this special case it can be shown that the trajectory of point A remains elliptical, but that it is a different ellipse.

In the general case, as is to be expected, the analysis is more complex, but could be evaluated numerically in our opinion in many cases. The development of such technology could, we believe constitute a valuable tool in the design optimization of the tolerances in mechanical components and systems, so that in addition to experience (which will always be essential) a quantitative estimate for the effects of tolerances and clearances could be developed. This in turn can lead to the rational optimization of tolerances in the design stage.

PART B

RESEARCH OF DR. DAVID A. HOELTZEL
AND GRADUATE STUDENT

## STATEMENT OF PROBLEM STUDIED

We have undertaken the development of a planning system shell for mechanical design. The objective of developing such a shell is to create a computer-based model of machining process planning and mechanical assembly planning that can be invoked during the early stages of the mechanical design process. The expected outcome of this research is the development of an AI-type planner (software-based in LISP with an X-Windows-based GUI) capable of providing guidance to mechanical design engineers on manufacturability of the machines they are designing. The system is to be used in a concurrent engineering environment for evaluating machinability and assemblability of mechanical designs during the early stages of the design process.

## SUMMARY OF THE MOST IMPORTANT RESULTS

The system which is actively under development is called PLASM {Planning System Shell for Mechanical Design}, and incorporates a planning engine based on nonlinear planning theory and constraint-based reasoning. The representation scheme for the planning engine uses productions and structured inheritance (SI) networks. The input to the planner is a feature-based geometric product model. The output from the planner is a set of manufacturing operators and sequential constraints.

The system generates a trial machining plan and assembly plan for a geometric model. The nonlinear planner detects conflicts in the manufacturing process plan and suggests resolutions for them for the generation of the final machining and assembly plans. The overall system architecture is shown in Figure 4. Specific details concerning the planner are discussed in our paper entitled "A Nonlinear Machining Process Planner for Concurrent Mechanical Design" which is to be presented at the 1993 ASME Design Automation Conference.

We have also undertaken an analysis of the computational efficiency of nonlinear planning in comparison with linear planning, and have determined the conditions (problem size) for which nonlinear planning becomes more efficient than linear planning.

Finally, we are currently writing an additional paper based on this research concerning the development of a knowledge base for machining process planning.

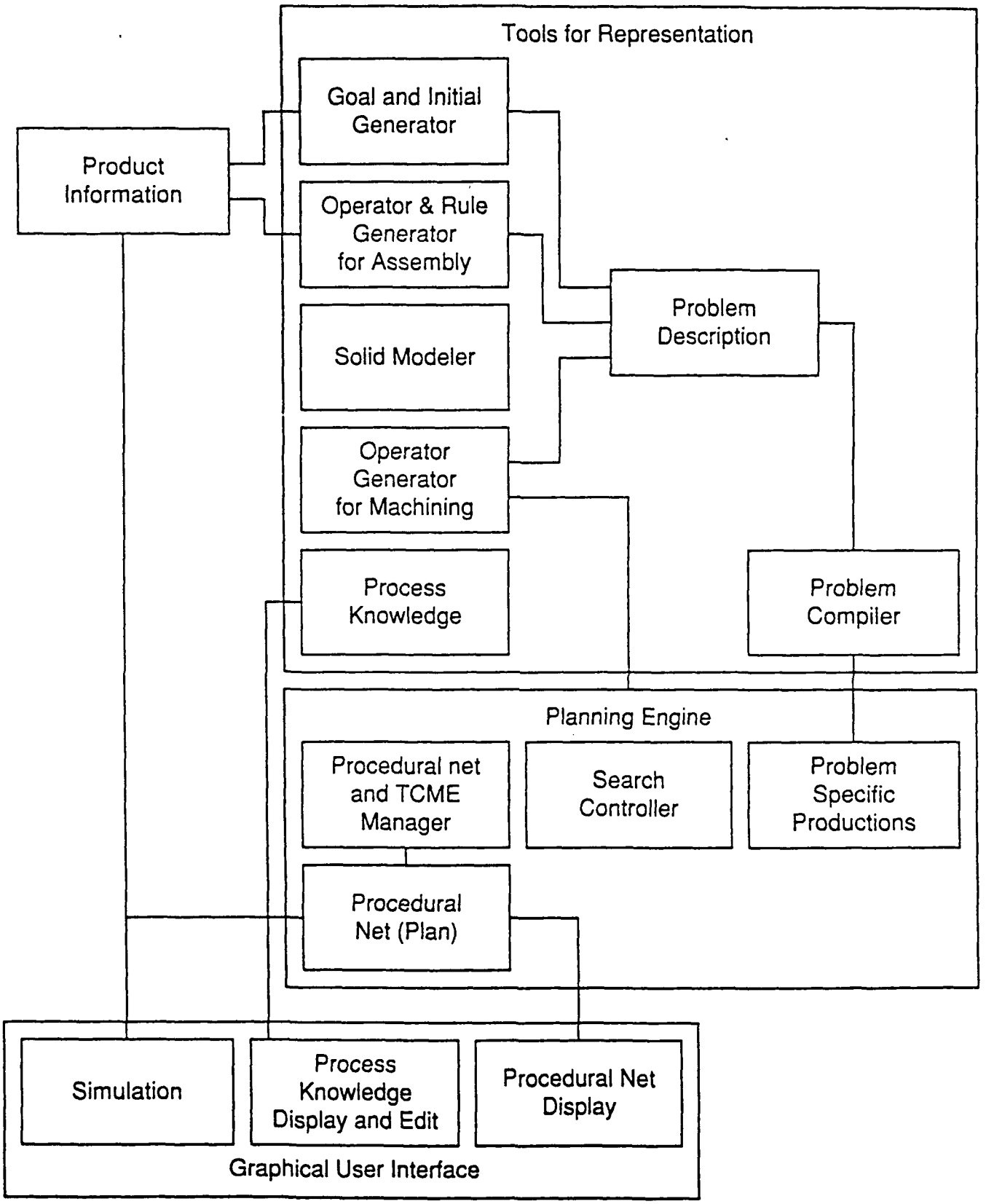


FIG. 4: SYSTEM ARCHITECTURE

List of Participating Personnel and Advanced Degrees Earned while Working on Project

(i) Dr. David Hoeltzel (Co-Investigator)

(ii) Mr. Taro Ochiai (Doctoral student; Doctor's degree expected upon completion of the research and thesis defense).

PART C: PUBLICATIONS

(a) JOURNAL PUBLICATIONS

1. "Hybrid Symbolic-numerical optimization in mechanisms design for the elimination of redundant constraints" by D. A. Hoeltzel and W. H. Chieng, Trans. ASME, Journal of Mechanical Design, Vol. 113, 1991, pp. 110-123.

2. "Synthesis of RSCR mechanisms for four precision positions with relaxed specifications", by C. H. Chiang, W. H. Chieng and D. A. Hoeltzel, J. of Mechanisms and Machine Theory, Vol. 27, # 2, 1992, pp. 157-168.

(b) PUBLICATIONS IN PREPARATION

1. "Design of robotic end effectors with rigid and elastic elements, including automation of the displacement equations" by Don Lin (doctoral candidate) and Prof. F. Freudenstein; Part 1: Slider-crank mechanism, Part 2: Robotic end effectors.

2. "A quantitative approach towards the evaluation of the effects of tolerances on the output of mechanisms" by Professor F. Freudenstein.

3. "A nonlinear machining process planner for concurrent mechanical design," by T. Ochiai and D. Hoeltzel, publication scheduled in Proc. ASME Design Automation Conference, September 1993.

THE VIEW, OPINIONS, AND/OR FINDINGS CONTAINED IN THIS REPORT ARE THOSE OF THE AUTHOR(S) AND SHOULD NOT BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, POLICY, OR DECISION, UNLESS SO DESIGNATED BY OTHER DOCUMENTATION.